DETECTING EMERGING SINKHOLES WITH FWD TESTING
2014 FAA WORLDWIDE TECHNOLOGY TRANSFER CONFERENCE

By:
Carl A. Lenngren
Traffic and Roads
Lund University
Lund, SE-22100
Sweden
Phone: +4670 546-6942
Carl.lenngren@tft.lth.se

PRESENTED FOR THE
2014 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Galloway, New Jersey, USA

August 2014

ABSTRACT

A local settlement on a runway was raising some concern at the Visby Airport on the Baltic island Gotland. The unevenness was local but the extent, the depth, and the reasons for the distress were unknown. The objective was to use FWD data including time histories to detect areas prone to settlements. The testing was laid out as to cover settlement area. The spacing between tests was set up in 5 m intervals and some additional tests were done with larger in-between spacing to get a statistical base line for the field parameters. The following analysis consisted of a backcalculation of pavement layer moduli and an assessment of the layer dynamic properties by time histories. The time history evaluation can be plotted as a load-deflection graph. These have been calibrated to hysteresis. For the 70 kN load level the area outside the settlement displayed a dissipation of about 4 Nm, whereas the settlement showed a dissipation of over 20 Nm. Practically, this means that the settlement has not stopped and is continuing. A recommendation was made not to allow traffic near this area until further examinations. A thorough FWD testing of the airfield using this method was also recommended. As such the method seems promising in detecting emerging sinkholes at an early stage to avoid lengthy runway closures.

INTRODUCTION

Falling Weight Deflectometer (FWD) data have been used to analyze pavement bearing capacity since the 1980's. The testing suits the mechanistic-empirical design methods that are now used by many agencies throughout the world. For airport pavements the bearing capacity can be assessed for PCN determination. For rehabilitation and pavement management the E-moduli of the various pavement layers can be determined. Thus critical strains in the structure can be determined and be compared to what is called for by the traffic and climate conditions. In most cases a linear elastic model is being used at some design load. As the seasonal variation often has a large influence on the results, it would be a tremendous task to try to model every combination of load and weather over the design period. Therefore, the engineering approach is to find a representative load and calibrate it to actual variability by experience and empirical methods. Hence, the Mechanistic-Empirical model is used for practical reasons. In this model the FWD maximum load is used together with the maximum deflections from a number of sensors. The load per se is applied as to mimic the load of a passing wheel. The duration is in the range of 20 to 60 milliseconds for most FWD:s in the shape of a haversine wave. For runways shorter loads are preferably used as to mimic high speed traffic.

Even though the peak deflections only are used in the evaluation process, most data from tests are saved in time history files. Primarily, consultants are looking at these files as a quality control measure. In the field, the operator may detect faulty sensor behavior, and the pavement engineer could discriminate between good or bad data in the further elastic analysis. In recent years, the time history traces have been used in research to evaluate tests during construction as described by the present author in [1], and for evaluating the rolling resistance induced by various pavement materials, Fäldner and Lenngren [2]. As sustainability is becoming a concern during the construction phase, it is important to also include the carbon footprint during the user phase. Thus, if one pavement type incur lower rolling resistance it can be selected in lieu of a higher carbon foot print during construction than the alternatives.

Anyway, as data storage is of less concern, most FWD tests nowadays are stored in files with the time history sampling and could be used for a more advanced evaluation when needed. By plotting load and deformation as the test progresses a hysteresis curve is formed and the energy losses can be estimated.

OBJECTIVE

The objective of the present paper is to investigate the dynamic response of FWD tests on sinkholes and if emerging sinkholes could be detected at ordinary testing.

SCOPE

Only the FWD dynamic analysis is presented in the case study, even if it also suggested other means such as ground penetrating radar or surface wave analysis.

CASE STUDY

A local settlement on a runway was rising some concern at the Visby Airport on the Baltic island Gotland. The unevenness was confined to a small area near the shoulder. The extent, depth and the reasons for the distress was unknown.

The island Gotland is the largest island in the Baltic Sea with a size of 3 200 km^2. The island population is about 57 000 inhabitants. It attracts many tourists and other visitors during the summer months, arriving by ferry or air. Apart from the tourism there are quarry industries, and lime and cement is being exported, almost exclusively through sea ports. All across the island the top soil is primarily resting on lime stone. The airport area is no exception. The air field was constructed in 1942 and sinkholes were then identified over the entire airport area according to the construction drawings.

The runway is 2000 meters long and 40 m wide with a flexible pavement. The number of operations is about 12 000 on an annual basis. Most traffic is civil, but the field also has military capabilities used when needed.

When the settlement was first spotted it was decided to use FWD data to determine the depth and extent of the distress. At the time there was some uncertainty about this being a single event and if it was spreading over a larger area. It was also decided to use time histories to detect areas prone to settlements.

TECHNICAL APPROACH

A picture shows the depression to be almost circular in shape with a diameter of about 2 meters (7 ft.). The maximum depth being about 25 mm (1 in.). The round appearance suggests that the deformation did not occur near the surface. See Figure 1 below.

FWD TESTING

An FWD was brought to the island on 29 August, 2013 and the testing took place in the afternoon by teatime. The pavement temperature was recorded to 29.7 to 27.1 degrees C as the test progressed. The testing was laid out as to cover settlement in three different line passes. One line passed the center of the distress, and two parallel lines were also measured two meters apart on either side. The spacing between tests was set up in 5 m intervals and some additional tests were done with larger in between spacing to get a statistical base line for the field parameters. The following analysis consisted of a backcalculation of pavement layer moduli and an assessment of the layer dynamic properties by time histories.

Figure 1. Distress photograph after rain shows lots of standing water in the puddle. Photo courtesy of Swedavia.

RESULTS

The backcalculated moduli could reveal the distress itself, by studying the layers at any given depth. The distance to bedrock was found to be rather shallow or about three meters only. As such the bedrock provides excellent bearing capacity.

In Figure 2 E(1) shows the backcalculated asphalt concrete layer modulus by software CLEVERCALC 4.0 along 300 meters of the runway and over the distress centered on the distance 100 m. As can be seen the elastic modulus drops remarkably over the depression, which is a telltale sign of a cracked layer. Then it fluctuates in a symmetrical fashion around the distress. The readings at 200 and 300 meters are lower than the ones at 0 to 80 m which could be due to past maintenance actions. The higher sections are further away from the threshold so the stiffness difference may be deliberate.

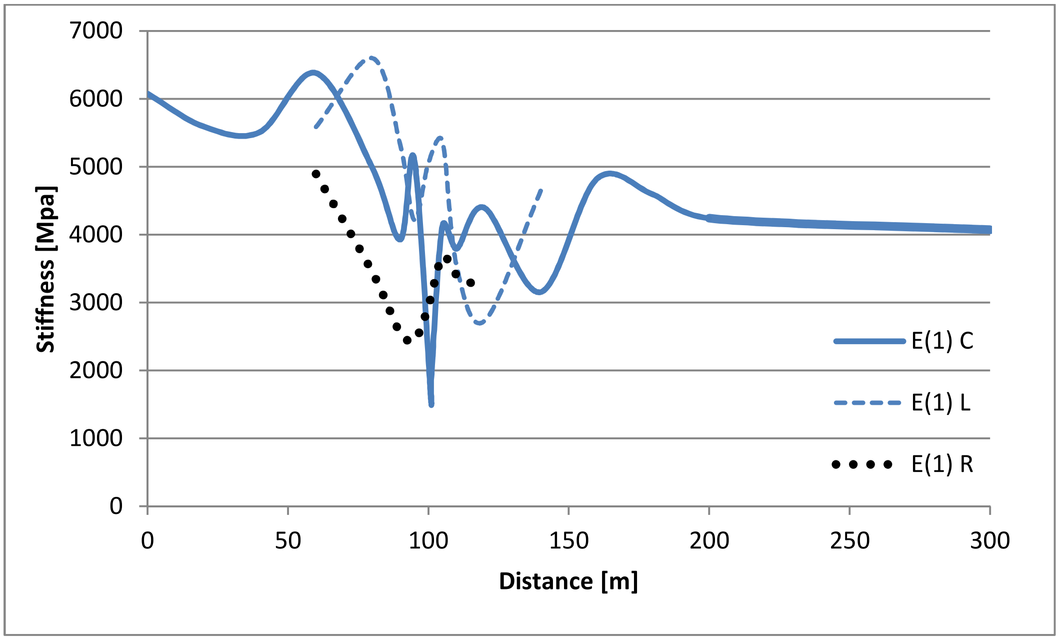

Figure 2. Asphalt concrete stiffness along the runway and over the distress

The unbound layers at depths from .20 to 1 meter are usually backcalculated to a stiffness of about 300 – 500 MPa. Right over the distress the modulus drops to 100 MPa only. The measured line to the right is also lower, but the minimum is about 200 MPa. The left line also has a minimum near the distress but is significantly better, see Figure 3.

A subgrade layer between depths of one to three meters was also backcalculated to a stiffness of about 500 MPa. However, there was a dip in the stiffness right under the depression to about 300 MPa. No significant differences were found for the adjacent lines on either side of the distress.

The linear elastic layer backcalculation showed a root mean square (rms) error per sensor of 2 % for a four layer system. Even though such errors are acceptable for overlay design methods, it is still indicative of the limits of the model. Usually, the rms is less than 1 % when the layer thickness data are known.

The bedrock is stiff, but the two distinct minima are seen before and after the distress at sections 95 and 110 meters respectively. On the left side the minimum is found by the distress and on the right side the values are lower as you go by it. This might reflect cracks or other deterioration of the lime stone. Thus a crude 3D picture was created of the stiffness in the ground. However, the momentary elastic stiffness does not really reflect the rapid occurrence of sink holes, even though the phenomenon might have a common cause as the stiffness. Hence, other parameters were sought for a better description of the cause.

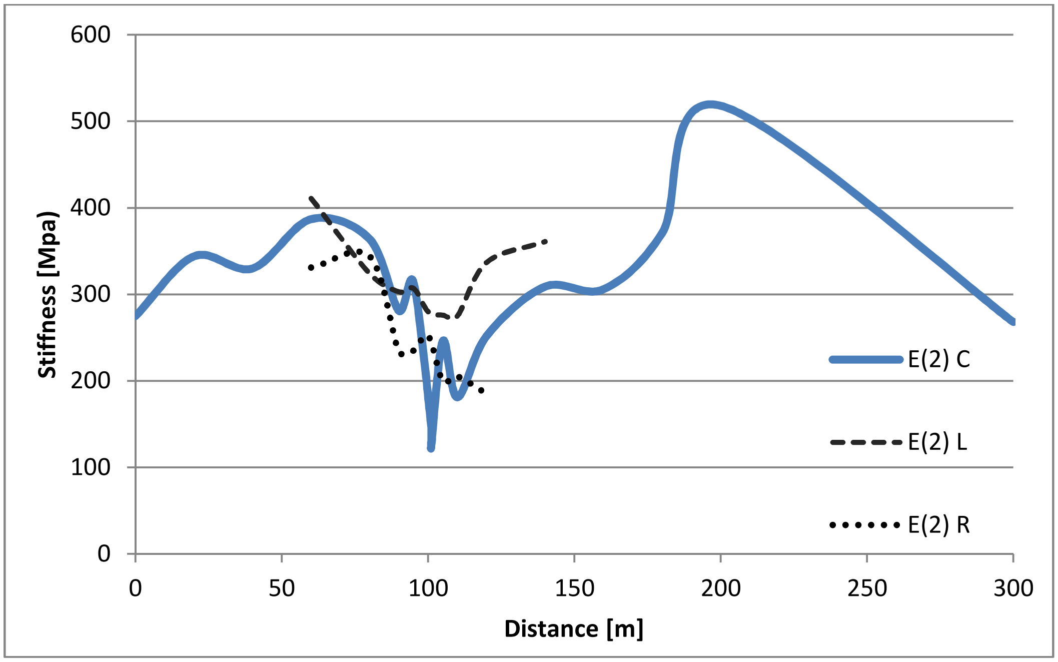

Figure 3. Unbound layer stiffness along the runway and over the distress

DYNAMIC EVALUATION

FWD software have been able to store the traces of load and deflection over time since the data sampling media devices became large enough about two decades ago. The plots serve as quality control tools for detecting faulty sensors or identifying non-linear behavior. Figure 4 shows a plot in the time domain with the load peaking first and then consecutive peeks from the deflection sensors from load center and outward. Rather early the results were used to also determine the master curve of asphalt concrete materials. Software for this was developed by Magnuson [3]. Pavement contribution to rolling resistance and quality control measures during construction has also been useful applications of the traces.

In Sweden the dynamic evaluation started with a project validating a Rolling Wheel Deflectometer Meter (RDM) in the mid 1990:ies, as described by Andrén [4]. Over 100 pavement sections were tested and compared with FWD data. Time histories were sampled from the FWD tests so the effects of truck speed on deflection could be assessed. The influence of the vehicle speed on the deflections was high as expected on asphalt concrete pavements. Other factors affecting the shape were the pavement type, but also the unbound materials and the subgrade properties had a large influence on the shape of the curves. Over the years following the present author has been investigating how the load-deflection curves can be utilized for construction control [5], rolling resistance [6], and initial rutting in asphalt pavements [7]. Thousands of deflection basins have been analyzed over the years, and some of the possible uses are summarized in [8].

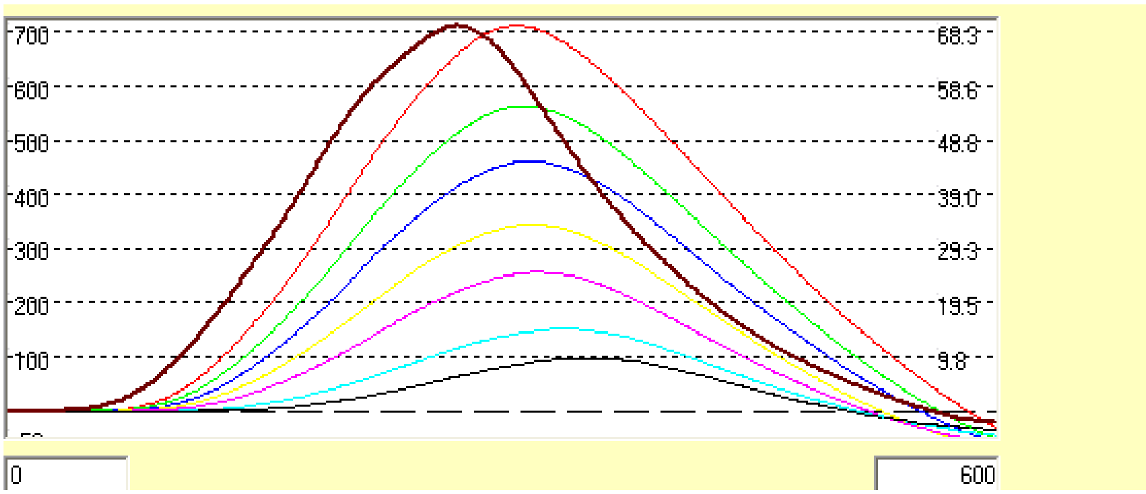

Figure 4. Load and deflection traces over a 600 millisecond interval. Left Scale is deflection in mu. Right scale is the load in kN.

The time history evaluation can be plotted as a load-deflection graph. An example from a rigid pavement is shown in Figure 5. Seven deflection sensors at different offsets are plotted versus the load. Note that the difference between the sensors is relatively small, which means that the slab is distributing the load over a large area. The load-deflection loops have been calibrated to hysteresis by fuel consumption tests. The center loop hysteresis in Figure 5 corresponds to a work of about 2.5 Newtonmeters.

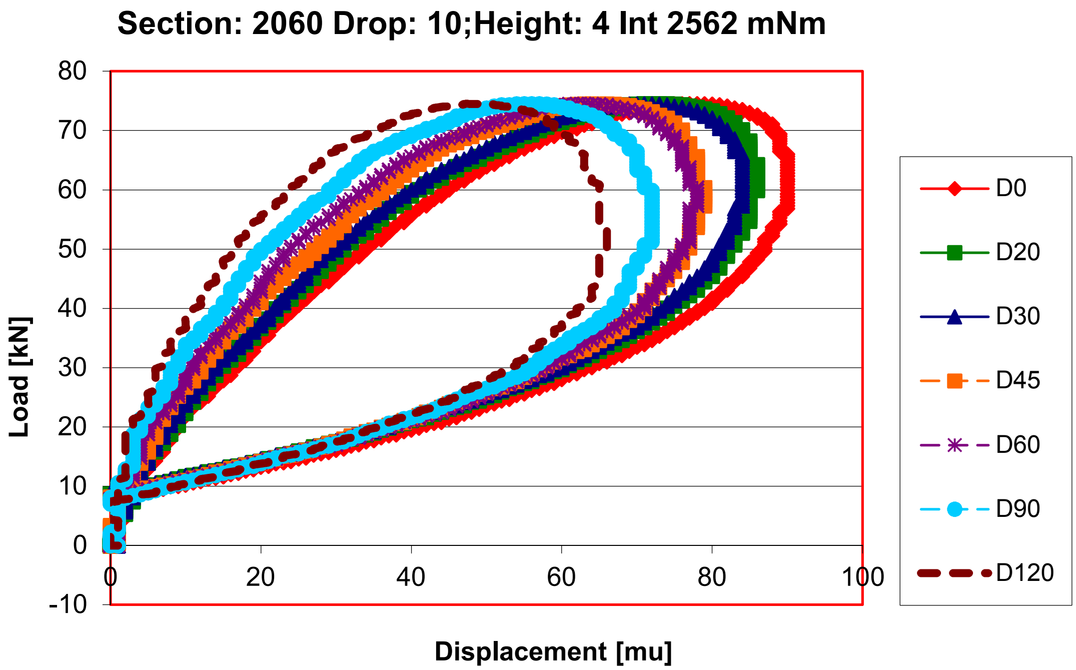

Figure 5. Load Deflection Diagram Example from a Rigid Pavement.

Figure 6 shows a center deflection graph from a flexible pavement at 40 degrees Celsius. Note that the curve is much less symmetric and that the deflection is increasing for a long time after the load has reached its maximum. In fact the maximum deflection occurs when the load is at about a third of the maximum value.

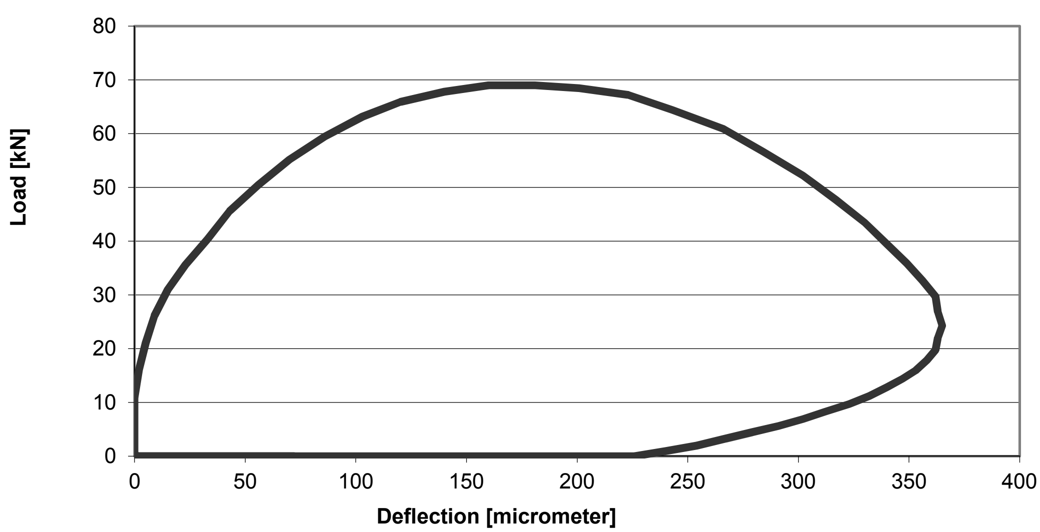

Figure 6. Load Deflection graph from a warm flexible pavement.

Over the years the present author has analyzed several thousand load deflection diagrams. In addition to assessing pavement rolling resistance properties, and asphalt concrete master curves, the curves are helpful in deriving other non-elastic behavior. Moving water and plastic deformation are two critical parameters that can be used for construction control of compaction for instance, see Figure 7. Note how sensor at 120 cm (leftmost curve) is pushed up by moving water.

There are many reasons for non-linear elastic behavior, but some have been identified and assessed by changing the input conditions.

1. Flexible pavement **visco-elasticity**, can be assessed by changing the temperature and/or the load frequency.
2. Unbound **layer damping**, is a function of the compaction level. Increased compaction lessens the loop area.
3. The influence of **inertia** increases with shorter load pulses. For rise times longer than 25 milliseconds, the influence is small.
4. Water in **saturated soils**, will influence the hysteresis loop, much like the poorly compacted soils. However, the outer sensors will heave as the water is being pushed away from the load.

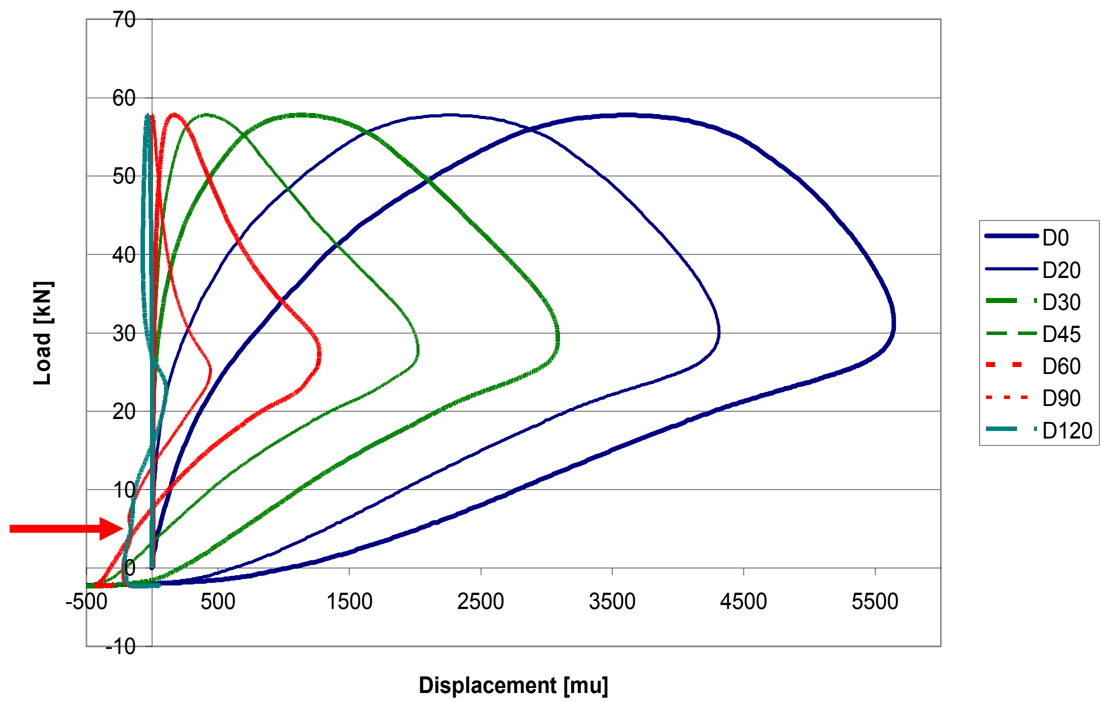

Figure 7. Moving water pushes the outward sensors to a heave, see arrow.

With this in mind the Visby airport distress was analyzed. For the 70 kN load level the area outside the settlement displayed a dissipation of about 4 Nm. This is what you would expect from a flexible pavement resting on a stiff subgrade. Figure 8 shows the plots from the section at 95 meters. The outer sensors at 90 and 120 cm from the center of the plate show an almost elastic response. These sensors are not affected by the asphalt concrete visco-elastic properties as their response is depending on deformation beneath a meter or so from the surface only.

Figure 9 is drawn to the same scale as Figure 8, but obviously the response is very different. The center sensor loop corresponds to a dissipation of almost 21 Nm, this is rarely seen on any paved road, and such high values were not encountered previously on an airport runway.

Of all the thousands of time histories analyzed so far, the shape of the curves from the depression is indicative of poorly compacted unbound layers. However, this large dissipation was never encountered before on a asphalt concrete pavement.

Somehow it seems the material is disappearing in cracks in the lime stone underneath. In reality, this means that the settlement has not stopped and is continuing as the dissipated work is much larger than visco-elastic contribution. The settlement at the time of measurement was too large to permit any traffic over it. A recommendation was made by the consultant not to allow traffic near this area until further examinations. As the settlement was near the shoulder, the shoulder line was moved into the runway.

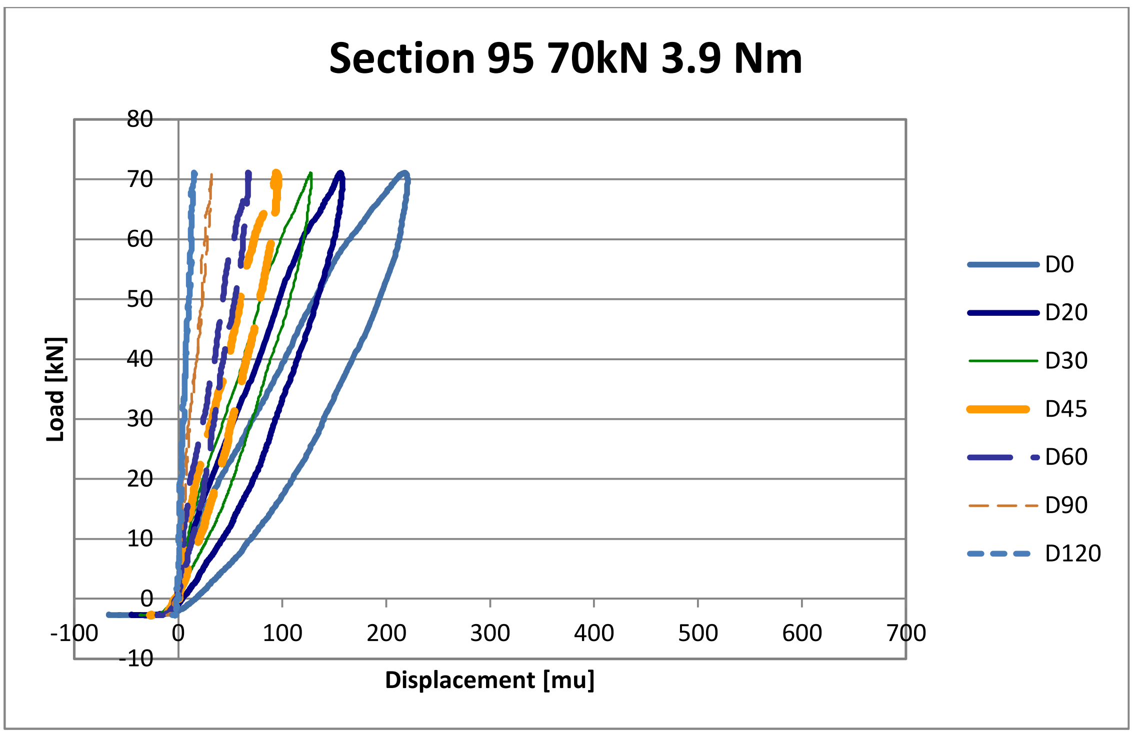

Figure 8. Load-Deflection graph five meters from the settlement shows good support and a normal dissipation of energy 3.9 Nm from visco-elastic cycle in the asphalt concrete layer.

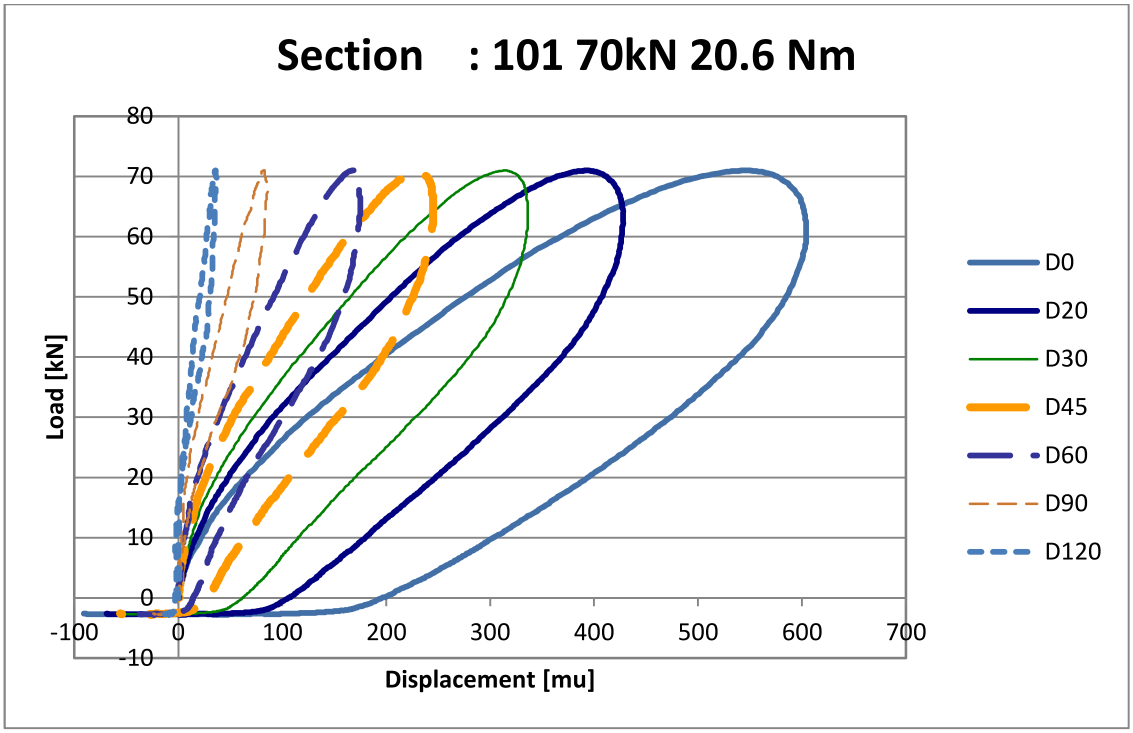

Figure 9. Load-Deflection graph near the depression. A large deformation and corresponding dissipation was found.

RECOMMENDATIONS TO GO FURTHER WITH THE CASE STUDY

Longitudinal profiling with a laser surface tester was recommended. It has been done successfully and by using the TAKE-OFF software showed that the detected depression was too large to allow any airplane operations. Fortunately, no other areas were detected closer to the centerline. However, the shoulder was widened to keep movements away from the depressed area.

A thorough FWD testing of the airfield using this evaluation method was suggested to detect other emerging sinkholes. By the time of the paper deadline, it remains to be seen whether a complete FWD survey would reveal any other areas with a high dissipation of the unbound material. As for the pavement repair, a surface overlay only is not recommended. The unbound material underneath is not compacted enough to support the pavement. Some form of stabilization could perhaps stop the loss of material, and concrete injection has been suggested. To investigate the extent of the sinkhole downward, low frequency ground penetrating radar could be used as cracks would hold water.

OVERALL CONCLUSIONS FOR FWD AIRFIELD TESTING

The FWD-testing storing time histories does not take any extra time, nor does it require any extra equipment to acquire the load-deflection graphs. All that is needed is a dynamic calibration of the sensors. The author strongly recommends doing this type of analysis as so much extra information can be derived from it. Software presenting graphics is very useful for the analysis. In this case an application was written for exporting the data to Microsoft Excel and for facilitating writing reports for the clients. The asphalt concrete hysteresis part can be determined by solving the master curve as suggested by Magnusson, [3]. The remaining part can mostly be attributed to permanent deformation in unbound layers. A quality check will reveal unusual deformations as a result of freely moving water.

REFERENCES

1. Lenngren, C.A. *Using falling weight deflectometer data for new construction interactive design.* Bearing Capacity of Roads, Railways and Airfields. Proceedings of the 8th International Conference (BCR2A'09), June 29 - July 2 2009.
2. Fäldner L.,Lenngren, C.A. *Pavement Type Hysteresis and Truck Rolling Resistance.* Bearing Capacity of Roads, Railways and Airfields. Proceedings of the 10th International Conference on Concrete Pavements Quebec, Quebec 2012.
3. Magnuson, S.H., Lytton, R.L., Briggs, R.C. *Comparison of Computer Predictions and Field Data for Dynamic Analysis of Falling Weight Deflectometer Data.*Transportation Research Record 1293. Pp 61-71. Backcalculation of Pavement Moduli 1991.
4. Andrén, P. (1999) "High-speed rolling deflectometer data evaluation." *Nondestructive Evaluation of Ageing Aircraft, Airports, and Aerospace Hardware III.* Proceedings of SPIE. Ajit K. Mal Editor Volume 3586, pp 137-147.
5. Lenngren, C.A.**"***FWD testing as a construction control tool*" Proceedings of the 9th International Conference on the Bearing Capacity of Roads, Railroads and Airfields, 2013
6. Lenngren, C.A. "*Different Pavement Types and Rolling Resistance*" Proceedings 2014 International Concrete Sustainability Conference Boston, May 12-15, 2014
7. Lenngren, C.A., Mårtensson B. **"***Comparing Design Strain to Actual Strain on New Roads*" Proceedings of the 9th International Conference on the Bearing Capacity of Roads, Railroads and Airfields, 2013
8. Lenngren, C.A. "*Going beyond elastic response while evaluating falling weight deflectometer data*". Bearing Capacity of Roads, Railways and Airfields. Proceedings of the 8th International Conference (BCR2A'09), June 29 - July 2 2009.